PIECES TO A PUZZLE: AIR–SURFACE EXCHANGE AND CLIMATE

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We all depend on the earth's climate. The climate, in turn, is strongly influenced by the atmosphere's turbulent exchanges with the oceans, solid earth, and biosphere. With GPS technology, we can measure this exchange at significantly reduced costs compared with earlier airborne systems, enabling us to bring many more observations to bear on the complex climate puzzle.

The earth's climate has never been constant. It is a subtle resultant of influences as diverse as the sun's convection patterns, continents' positions, and atmosphere's chemical composition. We humans have recently joined this list of effects.

The extent of our influence is controversial, because the quiet signal of climate alteration is hard to discern amid daily, seasonal, and yearly changes. It is generally agreed, however, that our large population and vigorous industrial and agricultural activities have detectable results.

To understand climate, as opposed to weather, scientists look for slowly varying controls. Although some controls are imposed from outside the earth, many important ones occur in the oceans, solid earth, and biosphere. Their influence is transmitted to the atmosphere through air–surface exchanges of heat, moisture, momentum, and important trace constituents, including carbon dioxide. These interactions are difficult to quantify, given the phenomena's ephemeral nature and the considerable expense of measuring them.

Recently, however, at the National Oceanic and Atmospheric Administration/Atmospheric Turbulence and Diffusion Division's (NOAA/ATDD's) Air Surface Exchange Branch, we have been able to create powerful GPS-based measurement techniques that can be used from a small aircraft. The result is not only lower costs and more experiments, but also greater flexibility and improved wind determinations.

BETWEEN HEAVEN AND EARTH

Scientists express their understanding of complex systems, such as our earth's climate, through computer models that must consider processes in the atmosphere, oceans, soil, and biosphere. These regimes communicate by passing three properties across their common interface at the earth's surface: momentum, energy, and mass.

Momentum exchange with the surface is the drag on the atmosphere that slows the wind, generates ocean waves, and limits storm lifetimes. Energy exchange is primarily heat transfer, by which the surface warms or cools the atmosphere in which we live and, in turn, generates the winds. Mass exchange involves dusts and trace gases, among which water vapor and carbon dioxide are particularly important.

Though water vapor is the primary agent of the well-publicized "greenhouse effect," carbon dioxide is the primary enhancer of this outcome, through its anthropogenic increase during the past 200 years. Though carbon dioxide is a decidedly minor atmospheric constituent (0.04 percent), this increase has made understanding what scientists call the *carbon budget* particularly important in forecasting climates and ecosystems as well as developing informed energy-use policies.

Like any budget, the earth's carbon budget has income (*sources*), outgo (*sinks*), and stocks on hand (*storage*). However, the information available to this budget's human auditors has gaps. Though we know that 40–50 percent of the carbon dioxide released by combustion and deforestation remains in the atmosphere, and another 30–40 percent goes to oceans, soils, and plant biomass, we don't know where the remaining 20 percent goes. We call this the *missing carbon sink*.

This uncertainty is currently inhibiting our ability to simulate the annual increment of carbon dioxide in the atmosphere, which degrades our ability to assess potential future climates. The increment may vary from year to year, latitude to latitude, season to season. Major research programs designed to study these unknowns contain elements that aim to develop a quantitative understanding of the mass, momentum, and energy exchange between the atmosphere and the surface (see "Air–Surface Exchange and Its Measurement" sidebar).

Effective airborne techniques to observe air–surface exchange over large regions have been available for more than 20 years. Unfortunately, these have required large multi-engine aircraft with expensive, heavy inertial navigation systems, beyond the means of most organizations, including NOAA/ATDD. Furthermore, their great cost limits the number of hours they can afford to fly.

MEASURING THE WIND

Since 1989, NOAA/ATDD has been developing low-cost airborne techniques to measure air–surface exchange over diverse and remote surfaces, such as oceans, tundra, forest, and swamps as well as to average values over heterogeneous surfaces. Our challenge has been to measure a gentle upward drift of air moving 5 centimeters per second from an airplane flying a thousand times that speed.

Most of the airflow around the airplane clearly results from the craft's motion itself, not from the wind. To determine wind from any moving vehicle equipped with wind sensors, we must take into account the sensors' motion. By subtracting the ground speed and the airspeed vectors (which nearly cancel), we end up with a tiny resultant — the wind measurement. Figure 1 illustrates wind measurement in two dimensions. We must be careful, because small errors in calculating either vector will develop into a large error in the wind measurement. Even at a relatively slow flight speed of 115 miles per hour (50 meters per second), a 1-degree error in measuring pitch or heading causes a 1-meter-per-second error in the wind calculation.

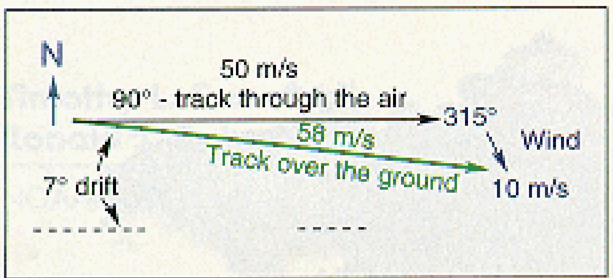

Figure 1. Measured from an airplane, wind is the difference between two nearly canceling vectors: the plane's track through the air minus the plane's track over the ground.

To further complicate matters, we must resolve atmospheric turbulence, composed of wind gusts no larger than a few meters across. This requires not only accuracy but also high frequency of aircraft position, motion, and orientation measurements.

THE WINDS OF CHANGE

To conduct our experiments, we had a small, revolutionary airplane, home-built from plans introduced by Burt Rutan in the late 1970s. The design of the plane, the Long-EZ, is safe and reliable and boasts many impressive characteristics. (Rutan would go on to design the Voyager, the first airplane to fly around the world without refueling.)

The Long-EZ is lightweight yet strong. It has a fiber-composite airframe that weighs only 950 pounds, and it is powered by only a 160-horsepower engine and can take off with a maximum gross weight of 1,800 pounds. The craft's aerodynamic efficiency allows it to travel as long as 10 hours at speeds of 200 miles per hour. With a maximum nonstop flight distance of 2,000 miles, the plane can reach research locations anywhere in the world. Typical cruising altitudes range from 8,000 to 18,000 feet. Equipped for instrument flight, the airplane can operate in a variety of weather conditions. A ballistic parachute enhances safety even at very low altitude. The airplane is inexpensive to operate and can be flown by a pilot-qualified scientist. Service requirements are minimal, enabling operation from small airports near the experiment sites.

We required a system to operate with the Long-EZ that would enable us to measure both the airplane and the wind velocities at least 30 times per second, accurate within about 0.2 meter per second. Although accelerometers can readily measure the airplane's motion accurately at this frequency, one must integrate acceleration to determine position and velocity. This accumulates error, requiring a low-frequency reference that does not drift from the true value.

Leading with Loran. Initially, we used atmospheric pressure for the vertical reference, and Loran for the horizontal. Mechanical gyros determined the airplane's roll, pitch, and turn rate. We integrated the turn rate using a magnetic compass (magnetometer) as a low-frequency reference. Our success with flux measurement for heat and moisture was sufficiently encouraging for us to continue development. The Loran and magnetometer, however, were accurate only over many seconds' average, and the old, heavy, power-hungry gyros stretched our small aircraft's capabilities.

Experimenting with GPS. About 1991, we began experimenting with GPS, using a single-channel GPS receiver backed up with Loran. With selective availability (SA) minimized for the Gulf War, the GPS position accuracy was readily within what we could independently determine (±25 meters), when enough satellites from the still-incomplete constellation were visible.

By 1992, with SA restored, we were using differential corrections, with five-channel

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Air–Surface Exchange and Its Measurement

Exchange at the earth's surface occurs by several means: biological, chemical, and physical. For example, vegetation removes carbon dioxide from the air in photosynthesis. This produces a carbon dioxide deficit near the leaves, relative to the rest of the atmosphere. Turbulent air currents, called *eddies*, replace this depleted air with air containing more carbon dioxide. Downward-moving eddies most likely bring air that has been away from the ground and is relatively rich in carbon dioxide. Upward-moving eddies usually carry air that has passed near the leaves and been depleted. On average then, more carbon dioxide is coming down than going up. At night, without photosynthesis, plants respire and emit carbon dioxide at the ground, so the process is reversed.

To measure this phenomenon, scientists need a representative sampling of the turbulent eddies to determine where air is rising and sinking and how much carbon dioxide, or other constituent, is present. The eddies may be only a few meters in size. Therefore, airborne sampling requires observing wind velocity and scalar quantities (temperature, humidity, carbon dioxide concentration) as often as 50 times per second. The exchange is the sum of products of vertical wind component with constituent concentration. For example, if sinking parcels tend to have a greater concentration of carbon dioxide than rising parcels, then the negative sign will prevail in the sum, indicating a downward flux of carbon dioxide.

Scientists can make such measurements from meteorological towers relatively easily, because the wind sensors are immobile. Eddies are carried past at the wind's speed, and researchers can thus sample them at a leisurely rate (10 times per second). From an airplane, this process is complicated because the sensors are moving and researchers are encountering eddies at a speed 10 times faster than from a tower.

receivers. When we could force the airborne and ground receivers (located in our hotel room, with the antennas outside) to track the same satellites, we obtained position accuracies within 10 meters.

Because high-accuracy, high-frequency GPS attitude measurement systems were not yet commercially available, we had to retain the magnetometer and gyros. Our measurements of heat and moisture fluxes easily showed the strong contrast between irrigated and native steppe land, during a study in eastern Oregon, and compared well with fluxes measured on stationary towers. Winds, however, were only marginally acceptable, and we were planning work in the Arctic, where our magnetometer would have difficulty finding magnetic north.

Breaking Through. We achieved a major breakthrough in 1993 when we purchased a six-channel, L1, C/A-code unit. This real-time, carrier-phase differentially corrected system with four antennas provided our first reliable, low-frequency reference for the airplane's attitude, particularly heading. The wind accuracies became acceptable for the first time, though still having about a 0.5-meter-per-second error.

O'ER PINES AND PERMAFROST

With our improved capabilities, we participated in measurement campaigns above the boreal forest around Candle Lake north of Prince Albert, Saskatchewan, Canada, and over Arctic tundra inland from Prudhoe Bay, Alaska, during the mid-1990s. We believe that remote regions, such as these, may hold one key to unlocking the mystery of the missing carbon sink. Given these harsh research environments, scientists are only beginning to extensively measure the air–surface exchange of water vapor and carbon dioxide using improved techniques, such as GPS.

Boreal forests occupy about 11 percent of the earth's land area, and the tundra occupies about 6 percent. The tundra alone stores 12 percent of the world's total soil carbon. These ecosystems are considered candidate storage sites for the missing 20 percent of global carbon emissions.

Furthermore, these regions are vulnerable to climate change. If the climate warms and dries from the introduction of greenhouse gases as predicted, the greatest warming will be over these northern continental ecosystems. Increased microbial and fungal respiration and decay of large carbon stores may provide a net source of carbon dioxide to the atmosphere.

GPS Capabilities. By this time, in 1994, we had two GPS receivers in the airplane, the six-channel unit for attitude, and a 10-channel L1, C/A-code unit for position and velocity. We were recording pseudoranges and Doppler shifts for differential correction by postprocessing with a 10-channel, L1, C/A-code ground unit. The equipment reported all GPS data, including attitude, approximately once per 1.5 seconds. We flew intercomparisons with towers and other aircraft during this experiment and found that our flux and wind measurements were quite comparable. We did have some extra variance in our vertical motion but reduced it, in subsequent experiments, with improved receivers reporting more frequently.

Forest Flights. The forest study, funded by the National Aeronautics and Space Administration, is called the Boreal Ecosystem–Atmosphere Study (BOREAS), and it sought to unearth the role of the boreal forest in the carbon and water budgets. The project involved more than 300 scientists from several nations, primarily the United States and Canada. Disciplines included ecology, botany, hydrology, meteorology, and mapping and remote-sensing sciences.

Participants measured air–surface exchange from four airplanes and several stationary towers. The ecologists and plant physiologists analyzed the photosynthesis, respiration, and various activities of the trees and other vegetation to help understand how these plant communities exchange carbon and water with the atmosphere. The towers detected exchange over homogeneous areas of the forest, while the aircraft covered more extensive regions, observing how the exchange varied with the change in surface terrain. The groves covered lakes and extensive areas of aspen, pine, spruce, and disturbance (burned or harvested).

Our involvement spanned the summer of 1994, from May to September, and about nine NOAA/ATDD scientists participated. Tim Crawford and Ed Dumas flew the Long-EZ on several predefined lines, one being 100-kilometers long, starting over an uncharacteristically large region of aspen, ending over spruce/pine, and crossing three significant lakes. The flight was at treetop level. Other flight patterns consisted of a set of short legs (10 kilometers) from multiple directions, crossing in the center at an instrument tower. The flights were at tower height and downwind to keep the airplane's exhaust away from the tower's carbon dioxide detector. An array of airborne sensors measured air turbulence (see Figure 2 and "Aboard the Long-EZ" sidebar).

Tundra Takeoffs. Operations over the north slope of Alaska, in collaboration with San Diego State University in California, began in 1993 and continued each summer until 1996. They also involved several stationary towers and physiological studies of area vegetation and microbial life. The plants and microbes are active only in the summer months, when the top 30 centimeters of soil, the "active layer" above the permafrost, is melted.

The Long-EZ had the only airborne flux operation during this project. Its small size and simple requirements were important assets at the small airport from which the researchers operated. The primary flight line stretched from the Arctic Ocean coast to the Brooks Range, about 180 kilometers, oriented north–south. At the low flight altitude in this remote location, normal radionavigation is ineffective. At the high latitudes, a magnetic compass must contend with rapidly changing declination angles and weak attraction to magnetic north. The featureless tundra offers few landmarks. For navigation alone, GPS was vital to our operation, keeping our flights consistently over the same straight ground track.

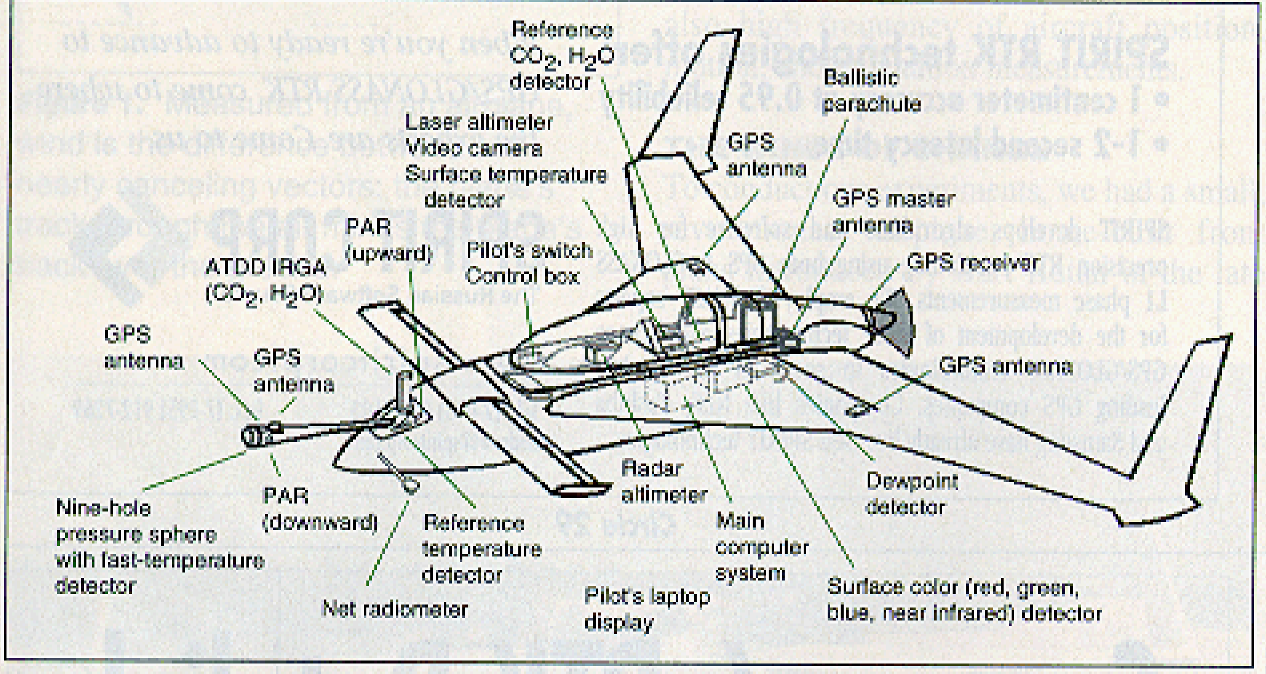

Figure 2. The Long-EZ is equipped with a slew of sensors for its climate studies.

Aboard the Long-EZ

The Long-EZ's unique shape results from careful aerodynamic optimization and is particularly well suited for atmospheric turbulence measurements. The forward lifting surface (called a *canard*) is designed to prevent stalls and spins. The winglets, smooth outer skin, laminar-flow wings, and pusher engine all contribute to the airframe's low overall drag.

A wind probe extending forward from the nose measures the relative airflow ahead of most of the flow disturbance. Figure 2 shows some of the many other sensors carried, along with the location of the GPS antennas.

These sensors include an infrared gas analyzer, measuring water vapor and carbon dioxide content of the air as many as 50 times per second. It passes a beam of infrared light through the airstream. Water vapor and carbon dioxide each absorb this light at different wavelengths. The amount of light absorbed is proportional to the number of molecules of each gas present in the air.

A net radiometer determines the amount (possibly negative) by which inbound heat and light, from above, exceed outbound. The Photosynthetically Active Radiometers (PARs) detect only visible light.

Various onboard air-pressure devices measure pressure differences on the gust probe. Airflow striking a sphere produces a known distribution of pressure over the sphere. By measuring the pressure at nine points on the sphere, NOAA/ATDD can determine the speed and direction of the oncoming air.

The craft also carries a commercial infrared gas analyzer (IRGA) to provide a low-frequency reference for our fast IRGA. Also for low-frequency reference, the aircraft contains an instrument that detects the dewpoint temperature, related to the amount of water vapor present in the air. The plane also includes a laser altimeter, a sensor of surface temperature, and a four-channel radiometer that can be set to match readings from several types of satellites. These remote-sensing instruments allow us to characterize the surface beneath the airplane for relation to the measured fluxes.

During a research flight, a single person operates the Long-EZ, with the rear seat occupied by a computer and instruments. The data system is highly automated, freeing the pilot to concentrate on flying the plane. Flights at 10 meters above ground for as long as six hours are typical. Because of the airplane's stability, this type of low-altitude flight is easy, provided the craft encounters no obstructions. Typical flight paths are straight lines as long as 100 kilometers. The pilot may fly this path back and forth as many as eight times in one day.

AIR–SURFACE ASSESSMENTS

Our excursions to remote, as well as nearby, ecosystems have helped us better understand what amounts of air–surface exchange are occurring from different regions of the globe.

BOREAS Results. Figures 3 and 4 illustrate air–surface exchange observed at midday along the 100-kilometer transect in Saskatchewan on July 21, 1994. By and large, the sun heats the ground and the ground heats the air. In Figure 3, the red line shows the solar radiation portion that heats the surface (net radiation). Some of this energy directly heats the atmosphere (sensible heat, blue), some evaporates water into the air (latent heat, green), and the rest is stored in the soil and vegetation (not plotted).

Much can be learned from such energy-exchange plots. The partition between sensible and latent heat is an important climate control, influencing how warm and moist the air will be over a region. Most striking is the large variability in exchange, much of which can be explained by the local surface. Lakes, in particular, appear as obvious minima, where sensible heat goes to zero or negative, while latent heat remains upward. Interestingly, the net radiation is highest over the lakes, even though they transfer little energy to the air. This reflects the tremendous heat capacity of water.

Different tree species produce clear variations as well. The aspen in the west add much more moisture than heat to the atmosphere, while the pines on the east provide more heat and less moisture. This was surprising, because much of the coniferous forest is in standing water. Generally, we found the boreal forest to put far more heat and less moisture into the atmosphere than we had assumed. This influences northern climate by generating deeper, drier, and more cloud-free atmospheric boundary layers.

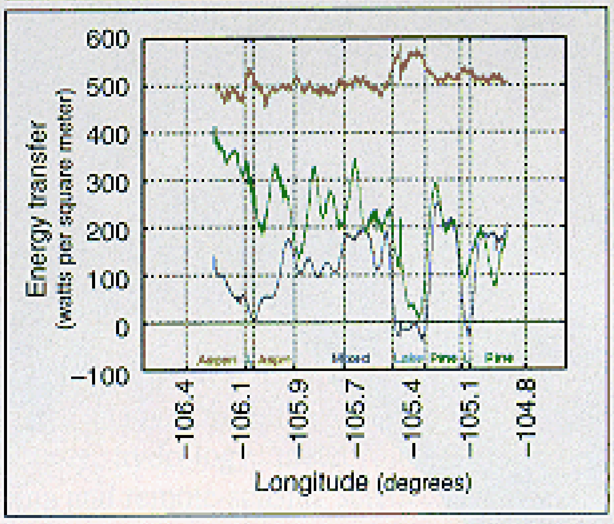

Figure 3. The solar energy input (red) goes to heating the air (blue) and to evaporating water (green). The remainder goes mostly into heating the ground (not shown). The partition of solar energy into heating and evaporation of water varies strongly and is an important control of climate.

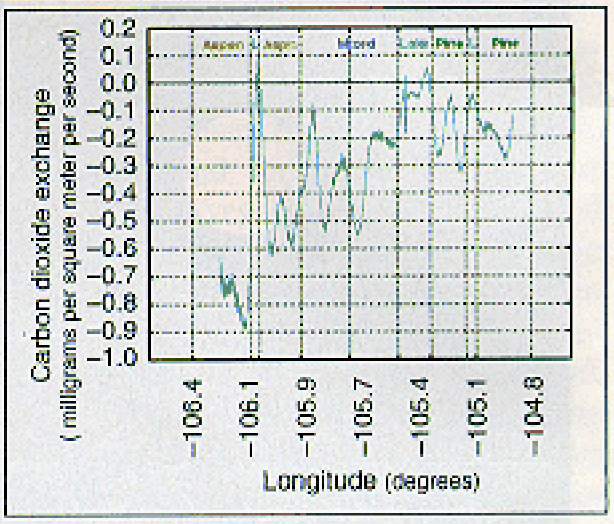

Figure 4. The exchange of carbon dioxide between the atmosphere and the earth varies strongly from place to place, depending on what is happening at the surface.

Figure 4 shows the variation of carbon dioxide exchange along the boreal forest transect. During midday, photosynthesis absorbs much of the carbon dioxide. The lakes, with near-zero carbon exchange, show as maxima. The strongest carbon uptake is by the deciduous trees, corresponding to their stronger evaporation of water. In general, the ongoing analysis is showing that the boreal forest is an important carbon sink but not necessarily enough to balance the carbon budget. The net carbon exchange is a small difference between photosynthesis and respiration, hence, vulnerable to small climate changes.

Alaskan Evaluations. The spatial structure of carbon dioxide exchange over Alaska's tundra is quite uniform, as expected from the generally homogeneous nature of the surface. The numerous lakes and other open water have been shown to provide slightly more carbon dioxide and methane to the atmosphere than the rest of the surface.

More interesting is the positive feedback with temperature. The Arctic tundra stores about 30 percent as much carbon as the entire terrestrial biomass (including tropical rain forests), most of it within permafrost. With warmer temperatures, the warm-season active layer above the permafrost is deeper and warmer, permitting more extensive anaerobic decay and release of carbon to the atmosphere. Photosynthesis absorbs some of this in the Arctic but is limited because of lack of available nitrogen.

Extending GPS Observations

Turbulent atmospheric motions range from kilometers to centimeters. Because eddies as small as a few meters across can still be significant, NOAA/ATDD samples 50 times per second, for an interval of about 1 meter. The GPS receivers report 10 times per second and are essentially noise-free up to frequencies of 1 Hz. This is remarkable, but not quite sufficient. The researchers extend the frequency range by sampling the measurement platform's acceleration in three dimensions, recovering the velocity, orientation, and position as time integrals.

Although GPS reports conveniently in earth coordinates, accelerometers do not. They operate in the platform's coordinate system — and in its reference frame, accelerated relative to earth. The solution is to convert each measured acceleration vector to earth coordinates before adding its contribution to the running tallies of velocity and position. This is a mathematical analog to the gyro-stabilized platform system in which a platform is held at constant orientation with respect to earth, regardless of the orientation of whatever is carrying it. For example, a video camera can be kept upright and free of jiggle even though it is on a ship in a storm. The process's starting point is to determine the platform's orientation, 50 times per second.

Clearly, this too requires accelerometers. Again, the GPS unit reports the airplane's attitude in different coordinates than those in which the accelerometers measure, though in this case the difference is negligibly small and ignored in practice. Researchers mount accelerometer pairs about four-meters apart and divide the difference of their measurements by the distance between them to yield an angular acceleration. Twice integrated, this provides an attitude angle. Vertical accelerometers, fore and aft, give pitch and, on each wing, yield roll. Lateral accelerometers, also fore and aft, provide heading. These acceleration-derived attitude angles are good for about three seconds' integration before error accumulates. With average GPS attitude measurements available each second, the entire range of aircraft's rotational motion can be covered. Figures 5 and 6 show the quality of the match between integrated accelerometers and GPS-derived pitch angle.

With the attitude determined, scientists can convert the measured platform acceleration to earth coordinates for integration, as required. Again, the error growth from the integration is negligible because of the short integration times made possible by the high frequency of accurate GPS measurements. Note that the airflow relative to the platform is also measured in platform coordinates. Researchers must also rotate this 50 times per second to earth coordinates so that they can remove the platform's motion with respect to earth and determine the turbulent wind measurement.

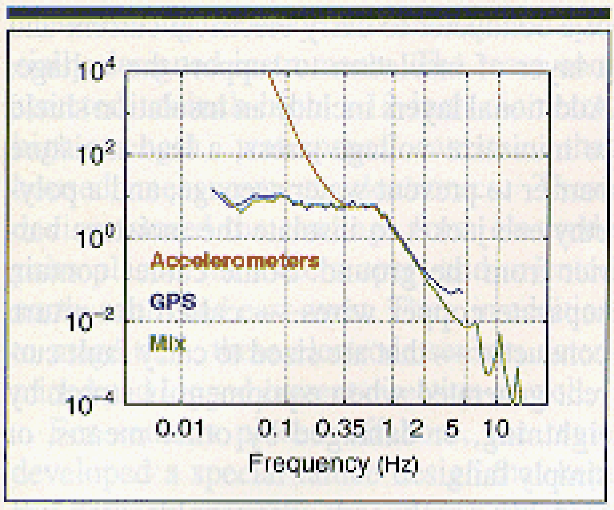

Figure 5. Spectral analysis of the data shows that the GPS-determined pitch angle of the airplane has no long-period drift and is accurately measured as frequently as 1 Hz. Integrated accelerometers, though useless for longer than about three seconds, can readily cover frequencies as high as, and beyond, 25 Hz. The mix uses the best of both systems.

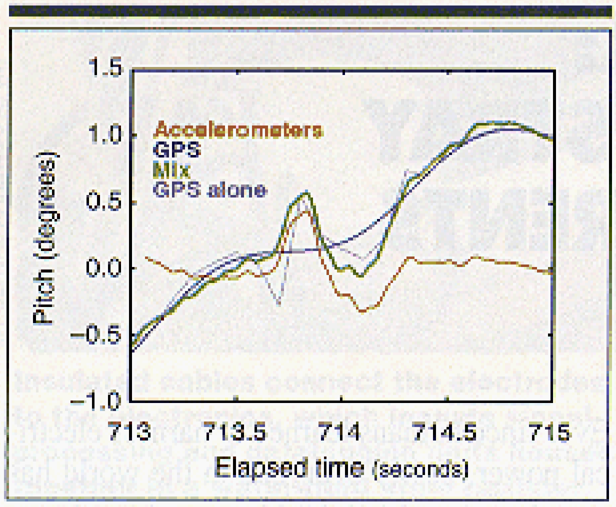

Figure 6 Even without accelerometers, GPS measures pitch angle remarkably accurately and frequently. To match with accelerometers, GPS is smoothed (blue), and the high-frequency signal from the accelerometers (red) is added. The result closely follows the GPS alone, but with higher time resolution and less digital noise. The close match, even at high frequencies, of the signals from these two fully independent measurement systems shows the great accuracy of GPS.

With still more warming, the upper layers of the ground may dry out, permitting oxygen to reach these layers, supporting efficient aerobic decay, which releases carbon dioxide more efficiently. The newly released carbon dioxide then contributes to further warming. Yet sufficient warming and drying may encourage growth of vegetation, increasing photosynthesis. As with all other aspects of climate, this is not a simple system.

EXPANDING CAPABILITIES

Recently, we implemented another upgrade that will help us interpret the mysterious language of climate. Since 1996, we have been using 12-channel receivers for both ground station and airplane. Counting antennas and cable, our two airborne GPS receivers weigh a total of five pounds and draw 10 watts. They operate on L1 with C/A-code, reporting pseudoranges and Doppler shifts 10 times per second. Our corrected GPS positions are accurate within about 3 meters (standard deviation). Velocities are accurate within 2 centimeters per second, horizontal, and 8 centimeters per second, vertical. We obtain aircraft attitude (pitch, roll, and heading) to 0.05 degree of arc.

We extend these high-accuracy GPS measurements with inertial observations to yield the airplane's position, motion, and orientation as often as 50 times per second, as required for turbulence studies (see "Extending GPS Observations" sidebar on page 38).

With this new system, we have been able to jettison the gyros and magnetometer. Although we now have a limit on how tight our turns may be without losing satellites (30 degrees of bank), we have a practical method fully capable of determining winds. It is particularly important that the equipment is portable on a small airplane, such as the Long-EZ.

AN OPEN HORIZON

GPS now allows research never before possible. Any operation requiring observations from a moving platform is enormously simplified by highly accurate measurements of the platform's position, velocity, and orientation. Air–surface exchange is just one application of airborne wind measurement.

Scientists studying pollutant transport near shorelines and in complex terrain will benefit from measuring turbulence and wind structures. Researchers investigating storms and other weather patterns can also avail themselves of airborne measurements of wind, temperature, and other parameters.

Beyond wind measurement, aircraft-based remote sensing is another possible application. In this kind of work, registration (that is, relating a data point to its precise spatial location) is important. Often, researchers register images by laborious coordination with identifiable targets, situated at known ground locations. Given precise knowledge of the aircraft's position and attitude, however, scientists can directly compute the data point's spatial location from its location in the image.

This year, we are remotely measuring ocean waves in a shoaling zone, using three precision laser altimeters sampling 50 times per second. The measurements will help us better understand the growth, movement, and decay of ocean waves in a setting where wave structure is particularly complicated.

Though we developed our technique for aircraft use, its applications clearly extend far beyond. The versatility, affordability, and portability of GPS has enabled us to create a high-frequency, high-precision method that is general enough to be applied to the kinematics of virtually any vehicle capable of carrying GPS receivers. A host of new applications awaits.

ACKNOWLEDGMENTS

Special recognition is due to David Auble, Robert McMillen, and Edward Dumas from NOAA/ATDD. David designed, built, and tested the required electronic circuits; Bob worked out computer problems associated with GPS hardware and the differential corrections; and Ed kept the hardware and software working together through many system configurations as well as flying about half the missions. Thanks also to Jeff Tonnemacher and John DeLucci of Trimble Navigation, who answered many of our perplexing questions. ■

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MANUFACTURERS

Timothy Crawford built the Long-EZ aircraft and its turbulence probe with data system, and Ron Dobosy developed the mathematical basis and much of the data reduction software. The airborne system requires three GPS units: one **Trimble Navigation** (Sunnyvale, California) Tans Vector, which supplies the 10-Hz high-accuracy attitude data; and two **NovAtel Inc.** (Calgary, Alberta, Canada) GPS Cards, which collect ground station differential correction data and onboard position and velocity information. The authors differentially corrected their data using C3NAV2 software from the **University of Calgary** (Calgary, Alberta, Canada). The earlier GPS units were single- and five-channel receivers from **Magellan Systems** (San Dimas, California). The mention of these products does not constitute an endorsement by the National Oceanic and Atmospheric Administration.